

UNCLASSIFIED

AD

401 581

*Reproduced
by the*

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

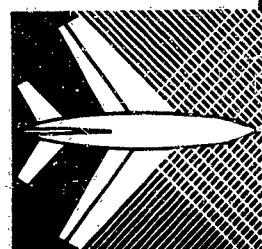
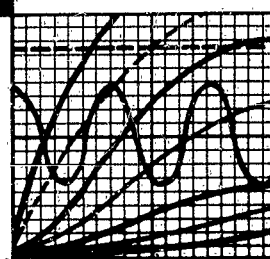
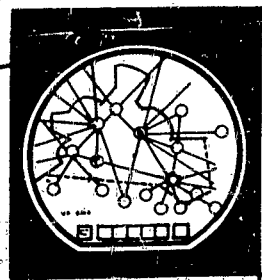
CAMERON STATION, ALEXANDRIA, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

63-3-2



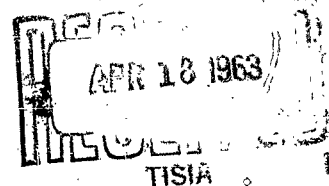
CATALOGED BY
AS AD NO. 401 581

4761-10-F (I)
Task No. 116-8R
(Portion of Phase 1)

STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAVIGATION TECHNIQUES

Volume I: Summary
Final Report

JAMES O'DAY
IRVIN SATTINGER
ROBERT SCOTT
JOSEPH SULLIVAN



401 581



Prepared by
NAVIGATION AND GUIDANCE LABORATORY
Institute of Science and Technology
THE UNIVERSITY OF MICHIGAN

December 1962

Federal Aviation Agency,
Systems Research and Development Service,
Research Division, Contract ARDS-436

4761-10-F (I)
Task No. 116-8R
(Portion of Phase 1)

STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAVIGATION TECHNIQUES

Volume I: Summary

Final Report

JAMES O'DAY
IRVIN SATTINGER
ROBERT SCOTT
JOSEPH SULLIVAN

December 1962

Prepared by
Navigation and Guidance Laboratory
Institute of Science and Technology
THE UNIVERSITY OF MICHIGAN
Ann Arbor, Michigan

Federal Aviation Agency
Systems Research and Development Service,
Research Division, Contract ARDS-436

NOTICES

Sponsorship. The work reported herein was conducted by the Institute of Science and Technology for the Federal Aviation Agency, Systems Research and Development Service, Contract ARDS-436. Contracts and grants to The University of Michigan for the support of sponsored research by the Institute of Science and Technology are administered through the Office of the Vice-President for Research.

Note. This report reflects the views of the contractor, who is responsible for the facts and the accuracy of the data presented herein, and does not necessarily reflect the official views or policy of the Federal Aviation Agency.

Distribution. Initial distribution is indicated at the end of this document.

Final Disposition. After this document has served its purpose, it may be destroyed. Please do not return it to the Institute of Science and Technology.

PREFACE

This report is a final summary of the investigations carried out during the period September 21, 1961, to July 31, 1962, by the Institute of Science and Technology of The University of Michigan for the Systems Research and Development Service, Federal Aviation Agency, under Contract No. ARDS-436, for the purpose of studying and analyzing four selected long-range navigation techniques usable by non-military ocean-crossing aircraft. The purpose of this report is to permit comparisons with other systems not considered in this study, and evaluation of systems considered in relation to desired track separation. The FAA Project Manager has been Mr. Nathaniel Braverman.

The Navigation and Guidance Laboratory of the Institute conducts work encompassing two general areas: (1) analytical and experimental research in navigation and guidance systems, techniques, sensors, and investigation of associated underlying physical and mathematical phenomena; and (2) supporting efforts in areas of work intimately associated with navigation and guidance. The Navigation and Guidance Laboratory, besides retaining its own staff of research personnel, is free to consult with and invite participation of members of the University faculty.

CONTRIBUTORS

Although it is impossible to acknowledge all of those who participated in this report, the authors wish to express especial thanks to the following colleagues:

Anderson, William	Kuipers, J
Conlon, Howard	Minty, George
Crabtree, Raymond	Porter, W. A.
Fedchenko, Robert	Puig, Hiram
Filkins, Lyle	Richardson, Wyman
Friberg, H. B.	Smith, Newbern
Jebe, Emil	Tirrill, Lloyd
Kazda, Louis	Vukovich, Joseph
	Young, Wendell

The authors also wish to acknowledge the valuable cooperation and assistance received from the staff of the System Research and Development Service during this study. We are particularly indebted to Mr. Nathaniel Braverman, Chief of the Technical Research Branch, for his technical direction, guidance and counsel. Mr. Charles Santora's contributions to the program, particularly in respect to very-low-frequency techniques, were very helpful. In his capacity as technical consultant to the Systems Research and Development Service, Mr. Nathan Marchand of Marchand Electronics Laboratory provided valuable assistance in the search for technical information and in the critical analysis of various navigation systems.

CONTENTS OF VOLUME I

Notices	ii
Preface	iii
List of Contributors	iv
Abstract	1
1. Introduction	1
1.1. Nature of Report	1
1.2. The Accuracy Problem	2
1.3. Statistical Description of Accuracy	4
1.4. Estimated Costs	7
2. Summary of Four Areas of Study—Preliminary Considerations	8
2.1. Summary—Heading References	8
2.2. Summary—Very-Low-Frequency Systems	15
2.3. Summary—Inertial Systems	18
2.4. Summary—Satellite Systems	19
Appendix A: Statement of Work	23
Appendix B: Letter Summary	27
References	31
Distribution List	32

CONTENTS OF VOLUME II

Notices

Preface

List of Contributors

List of Figures

List of Tables

Abstract

1. Introduction

2. Summary of Major Conclusions and Recommendations

- 2.1. Heading Reference Systems
- 2.2. Very-Low-Frequency Systems
- 2.3. Inertial Systems
- 2.4. Satellite Systems

3. Heading References

- 3.1. Introduction
- 3.2. Hybrid Systems
- 3.3. The Slaved Gyromagnetic Compass
- 3.4. Free Gyros
- 3.5. Heading Reference Derived from Celestial Information
- 3.6. North-Seeking Gyros
- 3.7. Variation Correction

4. Very-Low-Frequency Radio Navigation Systems

- 4.1. Introduction
- 4.2. Accuracy Evaluation
- 4.3. Lane Identification and Tracking
- 4.4. Transmitter Requirements
- 4.5. Problems of Introduction and Use
- 4.6. System Configurations Other Than Hyperbolic-Hyperbolic
- 4.7. Summary and Conclusions

5. Inertial Navigation Techniques

- 5.1. Introduction
- 5.2. Accuracy of Inertial Systems
- 5.3. Other Characteristics of Inertial Systems
- 5.4. Reliability
- 5.5. Economic Considerations
- 5.6. Timely Availability and Future Projections

6. Use of Satellites for Long Distance Navigation

- 6.1. Introduction
- 6.2. Transit Navigation Satellite System
- 6.3. Angle-Measuring Systems
- 6.4. Range-Measuring Systems
- 6.5. Conclusions and Recommendations

Appendix A: Radiation of Very-Low-Frequency Energy from Aircraft Antennas

Appendix B: Derivation of the d_{rms} Error of Hyperbolic-Hyperbolic,
Hyperbolic-Elliptic, and Rho-Rho Navigation Systems

B.1. Hyperbolic-Hyperbolic Systems

B.2. Rho-Rho Systems

B.3. Hyperbolic-Elliptic Systems

Appendix C: Correlation Coefficient Between Time Differences for a
Three-Station Fix

Appendix D: System Accuracy Contours for a Three-Station Hyperbolic System
on a Spherical Earth

D.1. d_{rms} Error on a Spherical Earth

D.2. Explanation of Accuracy Contours

D.3. Computation of Accuracy Contours with an Analog
Computer

D.4. Analog Computer Circuit

D.5. Conclusions

Appendix E: Description of the OMEGA and DELRAC Very-Low-Frequency
Hyperbolic Radio Navigation Systems

E.1. OMEGA

E.2. The Airborne OMEGA Receiver

E.3. DELRAC

References

Bibliography

Distribution List

STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAVIGATION TECHNIQUES

Volume I: Summary Final Report

ABSTRACT

The state of the art and the development potential of heading references, VLF (very-low-frequency) radio systems, inertial techniques, and satellite systems have been considered for their applicability to long-range ocean-crossing nonmilitary aircraft from 1965 to 1975. The navigation systems discussed here are by no means the only competitors for position and course determination over transoceanic and high-altitude transcontinental regions; our data and information should permit further comparison with other systems.

We conclude that magnetically slaved and good free gyroscopes will continue to be the principal heading references for commercial aircraft; we recommend improvement programs in magnetic compasses and the use of nonfloated friction-averaging gyros.

We do not expect that VLF systems will have been sufficiently operated to be acceptable for commercial aviation before 1975. However, their ability to cover large areas and inherent accuracy make them attractive if certain propagation and instrumentation problems can be solved.

In their present form inertial systems are competitive with doppler navigation systems, at least in accuracy. The choice of an inertial system for commercial flight depends on cost, reliability, and convenience. Product improvement and the recently lowered cost of inertial platforms may make these systems attractive in the near future, particularly for higher speed aircraft.

The present configuration of Transit, the only satellite reference system scheduled for implementation, exhibits time gaps which would be serious for aircraft use. The single-fix accuracy appears to be adequate if additional satellites are orbited to provide more frequent fixes.

1

INTRODUCTION

1.1. NATURE OF REPORT

This is the final report on contract ARDS-436, Study and Analysis of Selected Long Distance Navigation Techniques. It consists of a review of the state of the art and development potential for each of the several techniques studied. These are (1) improved heading references, (2) very-low-frequency ground-based radio navigation techniques, (3) inertial navigation techniques and

(4) navigation using earth satellites for nonmilitary ocean-crossing aircraft. An explicit presentation of the work program is contained in the statement of work of the contract, appended to Volume I.

The above techniques have been considered for their applicability to the high long-range traffic over ocean routes expected in the period 1965 to 1975. Principal attention was directed to routes terminating in the United States and its possessions, although some consideration was given to world-wide coverage for those systems which provide it easily. In an effort to describe the operational environment, information regarding current and future routes, aircraft types and schedules was collected.

Sources of information for work on this contract were many. While detailed references are given in following sections, it seems worthwhile to note here the variety of sources—military development agencies, several military operational units, many manufacturers and developers, several airlines and airline associations, and several military testing agencies. One major effect in connection with using such a variety of sources was the disparity of information regarding similar equipment or systems. For systems in the development state it is difficult enough to arrive at precise cost and performance estimates. For systems which exist only as proposals—or gleams in the engineer's eye—the cost and performance estimates must be made carefully and then viewed suspiciously.

This report is divided into two volumes. Volume I includes this introductory section, which discusses the approach to the problem; and a summary section, which presents conclusions and recommendations relative to each of the four areas of study. Appendix A comprises the statement of work of the contract under which this study has been conducted; Appendix B is a letter summary of the report's major conclusions and may be useful to the reader as a quick survey.

Volume II discusses the problem in more detail. After an introduction and a brief summary its four main sections take up heading references, VLF radio systems, inertial systems, and satellite-reference systems. Five appendixes discuss VLF systems in still more detail.

1.2. THE ACCURACY PROBLEM

Taking accuracy as a measure of performance of a navigation system, we find that various "kinds" of accuracy exist. These are not comparable although they are often treated as such in side-by-side comparisons of competitive systems. Common usage of "accuracy" may include any one of the following.

- (a) The fundamental accuracy limit for a particular system is determined by the physical limitations inherent in the method, or by our knowledge of the underlying physical

constants. For example, radar is limited by (among other factors) the knowledge of the propagation velocity of electromagnetic waves.

- (b) Ideal performance today is the accuracy attained by existing research and development systems under ideally controlled laboratory conditions. It also comprises predicted system performance based upon present-day component accuracy under laboratory conditions.
- (c) Ideal performance in the foreseeable future is the same as (b) except that an extrapolation is made to some future date. The prediction of improved performance is (or should be) based on normal research and development progress; breakthroughs cannot be programmed, and it should not be assumed that they will occur.
- (d) Operational accuracy is the accuracy of the production system operated, calibrated, and maintained by airline personnel in the field rather than by the design engineers. Operational accuracy is sometimes estimated by subjecting ideal performance results to some degradation factor.
- (e) Special operating condition performance refers to accuracy under unfavorable conditions which may further degrade the accuracy from (d). Included in this category are short warmup times, temporary power failures, high latitudes, etc. In some cases, special conditions may deny use of the system entirely.

Most statements on accuracy are given without due regard to the reliability of the system. Malfunctions or large inaccuracies for which specific causes are suspected are customarily removed from the statistical analysis of errors. Thus, quoted accuracy, even when based on field experiments, may not be a valid measure of system performance.

Most navigation systems require initial settings or calibration. These may take the form of null and scale adjustments, starting point or transmitter locations, and/or north reference direction. Conditions may limit the precision with which these operations can be performed. The result is that any system of a specified type—no matter how accurately it performs when correctly calibrated—may exhibit inadequate accuracy under normal operating conditions. We conclude that "system accuracy" must be interpreted in its broadest sense to include the effect of ground equipment, information regarding initial conditions, setup procedures, auxiliary data sources, and vehicle behavior.

The relation between ideal performance and field performance also deserves comment. It does not suffice to multiply ideal performance by an arbitrary degradation factor. To do so would be to ignore the reliability factor, which may favor a simple but crude system over a "more

accurate" system that is likely to be complex and delicate. Furthermore, the "more accurate" system will require complicated calibration and alignment operations as well as highly specialized maintenance procedures. When these are improperly performed under normal operating conditions, the basically "more accurate" system may do poorly in comparison with a crude and simple system. In other words, a comparison of the laboratory performance of two systems is insufficient to predict their comparative effectiveness under operational conditions.

In looking for civil applications deriving from military developments, we must realize that the civil operator has different performance requirements. In a military navigation mission, the problem might be to navigate with a precision of 100 yards 70% of the time, so that a bomb might be placed effectively. The military operator is willing (although perhaps not happy) to see a complete failure the other 30% of the time. Complete failure may mean missing the target by ten miles, or even the loss of the aircraft. While either of these undesirable results may be acceptable to the military, they cannot be tolerated by the commercial operator. In contrast, he would place much more stress on the reliability of the equipment—and thus the overall "performance" of a system—rather than its occasional spectacular accuracy.

It is sometimes a characteristic of very complex systems that "when they are good, they are very very good—and when they are bad, they are horrid." Important criteria, then, for civil navigation aids are their reliability and fail-safe characteristics. These criteria favor certain types of hybrid and redundant systems yielding consistent, even though mediocre, performance.

In this report we have attempted to report operational accuracy under normal flight conditions. In many instances, of course, data indicating such accuracy are not available, in which case notation is made as to the meaning of the "accuracy" information given.

1.3. STATISTICAL DESCRIPTION OF ACCURACY

In recognizing these general concepts of accuracy we must add that statistical terminology for describing the accuracy is, unfortunately, not standardized. First, the technical distinction between accuracy and precision is mixed in many presentations. For clarity we state here that precision merely means the repeatability of a measurement expressed in suitable terms. On the other hand, an accurate system is capable of measuring the true value of a quantity, or we say it is unbiased. The five common usages of accuracy listed above would ordinarily combine the assessment of bias and repeatability into one single accuracy figure.

In navigation terms we say a system is accurate if the average of a long series of fix determinations in the neighborhood of a target destination is this target's location. Such a statement,

however, says nothing about dispersion of the individual fixes, which is described by a precision measure.

The navigation problem increases the terminology confusion because of the increased number of parameters and the variety of available measures for describing the two-dimensional error structure. Thus, we find that the assessment of accuracy may include one or more of the following:

- (a) d_{rms} error
- (b) variance
- (c) standard deviation or standard error
- (d) moments of the radial error
- (e) root mean square
- (f) mean square error
- (g) CEP, the circular probable error

In the univariate (one-dimensional) case the first moment is taken about the origin and other moments are taken about the mean. The bivariate or two-dimensional problem again calls attention to moments about the origin when the radial error is considered.

The purpose of this report is to permit comparisons with other systems not considered in this study and evaluation of systems considered in relation to desired track separations.

Specifications of accuracy presented in this report are given in terms of the d_{rms} error, a parameter often used for this purpose. The interpretation of this statistical method of specifying accuracy (actually, precision) is briefly summarized in this section.

Consider a position-measurement process in which measurement errors along each of two orthogonal axes have a normal distribution and are uncorrelated. If the standard deviations of the errors along the two axes are equal ($\sigma_x = \sigma_y$), a circle with its center at the mean values of the position coordinates is the locus of points having constant probability density. It can be shown that the probability is 0.632 that a single position measurement will fall within such a circle having a radius of $d_{\text{rms}} = \sqrt{\sigma_x^2 + \sigma_y^2}$. For a circle of radius $2 d_{\text{rms}}$ the probability increases to 0.982.

In the general case of position determination the errors in x and y may be correlated, and σ_x is not equal to σ_y . For the bivariate (two-dimensional) normal distribution it is possible to make a transformation (consisting of a rotation of axes) which will remove the correlation of the errors. The distribution may then be described by two new variances along the two new orthogonal axes. In this general situation, an ellipse represents the locus of points having con-

stant probability density. The parameter d_{rms} , as defined above, may still be used to represent the spread of individual position determinations. This quantity d_{rms} describes the radius of a circle that is arbitrarily drawn, since the shape of the distribution in plan view is elliptical. Within this circle, however, the probability of obtaining a single position determination lies within a certain narrow range even though the ratio of the two standard deviations σ_y/σ_x (taken as the smaller over the larger) may be unknown in the range zero to one. Table I shows the range of probabilities for several circles. It seems most natural, perhaps, to employ the d_{rms} statistic for the uncorrelated case with $\sigma_x = \sigma_y$, but the maximum error is about 8% for the examples in Table I if $\sigma_x > \sigma_y$. The specification of positional error by a d_{rms} circle tends to simplify calculations, and it may be noted that such specification for a circle of $1.4 d_{\text{rms}}$ radius or larger is always conservative, in the sense that the errors are considered to be greater than they actually are. If improved values of the probabilities are desired, they can be read from available tables when the ratio of the standard deviation is known for the uncorrelated situation.

TABLE I. PROBABILITIES CONTAINED IN CIRCLES
OF VARYING RADIUS

Radius of Circle	Probability for $\sigma_x = \sigma_y$	Probability for $\sigma_y = 0$
1 d_{rms}	0.632	0.683
2 d_{rms}	0.982	0.954
3 d_{rms}	0.999	0.997

It is worth pointing out that most of the statistics used to describe the radial error distribution or the position determination distribution are inter-related; when one is known, others are readily obtained. This derivation is most easily made when $\sigma_x = \sigma_y$ in the uncorrelated case. Since this case is of interest for a variety of navigation problems, some of the inter-relations are given here. For the noncircular distribution case it appears preferable to consult suitable tables for describing the two-dimensional error situation.

In the navigation problem we take d as the radial error or the straight line deviation of the position determination from the true position. Hence, $d^2 = x^2 + y^2$ from the geometry of the situation. Thus, we find that d_{rms} may be described as the square root of the average value of d^2 . Other statistics that may be considered are the variance of d , the standard deviation of d , and the CEP. Taking $\sigma_x = \sigma_y = \sigma$ as indicated above, we show the relations among various statistics in Table II.

TABLE II. RELATIONS AMONG STATISTICS USED TO DESCRIBE THE ERROR DISTRIBUTION IN THE CIRCULAR NORMAL (TWO-DIMENSIONAL) DISTRIBUTION CASE

Name of Statistic	Value in Terms of $\sigma_x = \sigma_y = \sigma$	Equivalent d_{rms} Units (σ)
d_{rms}	$\sqrt{2} \sigma$	1.000
Mode of d	σ	0.707
Median of d	$\sqrt{1.386} \sigma$	0.833
Mean of d	$(\pi/2)^{1/2} \sigma$	0.866
CEP	$\sqrt{1.386} \sigma$	0.833
Standard Deviation of d	$\left(\frac{4 - \pi}{2}\right)^{1/2} \sigma$	0.463
Variance of d	$\left(\frac{4 - \pi}{2}\right) \sigma^2$	0.3035

In view of the frequent application of the d_{rms} statistic in the navigation literature and its general usefulness in the two-dimensional error problem, we have tried to present this statistic consistently when summarizing system or component capabilities. When other statistics are used (e.g., those indicated in Table II), we have tried to make clear their proper interpretation and their relation to the d_{rms} error.

1.4. ESTIMATED COSTS

For systems under development the problems of estimating costs are similar to those of estimating accuracy. In fact, even for systems in existence the acquisition cost can vary widely. A good example is the recent purchase by TWA of a dual doppler radar, supplemented by Edo Loran for 12 Boeing 707 aircraft. The doppler equipment included dual transmitter-receivers, dual sensor tracker units, dual control units, a single antenna, two computers, two computer controllers, and two indicators. Purchase cost of the dual DRA-12-A doppler radar navigation system is quoted by Bendix as approximately \$25,000. TWA's estimate of the cost of the program of installing 12 systems was \$1,800,000—or \$150,000 per aircraft. The apparent discrepancy is not hard to explain, but is worth some discussion to indicate the elements involved. In addition to the \$25,000 for the basic equipment, spares are needed. For an airline like TWA, which operates over long routes, appropriate spares may be more than 50% of the initial cost. In the case of this installation program, the 707's had to be modified by Boeing to accept the doppler antenna, the compass system had to undergo a very careful (and expensive) calibration,

and the installation of the equipment required the aircraft to be pulled from normal service for a period of time—thus causing a loss of income. The point of this example is that there may be many factors which must be considered in the cost of a particular system to the airline. These factors make a straightforward comparison difficult. While it has not been possible to consider all of them, many of them are discussed in connection with the various systems.

In general, cost figures presented in this report are best estimates for purchase of a small quantity of a developed item. In certain instances additional estimates are given for abnormal installation costs and developmental costs.

2

SUMMARY OF FOUR AREAS OF STUDY — PRELIMINARY CONSIDERATIONS

Unqualified statements on the merits of a particular navigation system are seldom valid. For example, dogmatisms such as "very-low-frequency radio systems are vulnerable to atmospheric noise and should be avoided" or "inertial system warmup requirements preclude their operational use" are unsound. A critical examination of the first of these may reveal that (1) by appropriate design smoothing circuits may make the effect of atmospheric noise negligible; or (2) the noise problem exists only in certain subtropical regions over land where other navigation facilities are available. The second quotation is misleading. Although inertial systems operating with short warmup times are subject to some sacrifice in accuracy, the reduced accuracy may still be adequate for the mission.

This report makes no attempt to compare specifically the various systems. The systems discussed here are by no means the only competitors for position and course determination over transoceanic regions. But the report presents data and information in a form which should facilitate comparison with competitive systems.

2.1 SUMMARY—HEADING REFERENCES

2.1.1. THE REQUIREMENT. An aircraft heading reference is a device by which the direction of the horizontal projection of the longitudinal axis of an aircraft can be determined. Such a device may itself be aligned with any of several directions (e.g. magnetic north, grid north, true north, or some other direction), but a useful device may always be referred to true directions on the earth's surface so that the aircraft may be navigated.

What is desired by present commercial operators in a heading reference system has been well expressed by Trans World Airlines in their crew training literature [1]:

- (a) Stability of indication in level flight and in gentle maneuvers
- (b) Practical solution of the problem of extreme convergency of geographical meridians at high latitudes, causing rapid and large changes in true course
- (c) Effective indication in areas where the horizontal component of the earth's magnetic field is weak; namely, in the polar regions
- (d) Elimination of the need for magnetic variation compensation
- (e) Capability of flying a great circle as a constant course instead of as a varying course

In addition, the heading reference must have an accuracy compatible with the along-course distance accuracy. For most purposes it is desirable for the total navigation error distribution to be approximately circular; thus, in the past, when aircraft ground speed was computed from computed true air speed and estimated winds, standard deviation errors of 2° to 3° were acceptable, although it was often not recognized that such errors existed. At any rate, with conventional dead reckoning methods compasses exhibiting errors of this order did not appreciably degrade overall performance of the navigation system.

With the commercial use of doppler radar the ratio of cross-course to along-course errors became unreasonably high [2]. Along-course accuracy of the order of 1% calls for a corresponding heading accuracy of about $1/2^{\circ}$, and it was evident from early commercial doppler flights that this value was not being achieved. Careful compass compensation by some airlines has resulted in reduction of the cross-course error to a value only slightly larger than the along-course error. Other airlines still report excessive cross-course errors [3].

Two factors will require an improvement in heading-reference performance in the 1965-1975 time period. First, with the increasing traffic over the North Atlantic there is a need for closer spacing of aircraft—both along track and between tracks. Second, the advent of Mach 2 aircraft will present a severe dynamic environment to the compass systems, and more sophisticated systems may be necessary to maintain the same navigational accuracy the subsonic jets achieve today.

Whereas systems with accuracies in the range from $1/3^{\circ}$ to 1° were considered in this study, there may be real value in striving for the lower end of this range. At 1800 miles $1/3^{\circ}$ is approximately 10 miles; if this is a $1-\sigma$ value, it is barely good enough to reduce current separation standards over long routes if fix correction en route is not possible.

2.1.2. THE PHYSICAL BASES FOR DETERMINATION OF HEADING. Heading of an aircraft on or near the surface of the earth can be derived from one or more of three basic sources: the observation of the celestial field, the earth's rotation, and the earth's magnetic field. While

there are errors in the various instruments which determine direction from these sources, there are some inherent limitations in the sources which deserve mention.

Celestial heading references are, for the most part, quite stable. Visual detectors, however, are limited by cloud cover and, in many cases, by knowledge of the vehicle's position on the earth. Ability to determine direction from a celestial reference is a function of the angular elevation of the celestial body (i.e., if the body is at 90° , direction is indeterminate, and near ninety degrees any instrumentation error is seriously expanded).

One additional source of heading information which is useful if not "basic" is the determination of track made good by intermittent fixes. When a doppler radar is aboard the aircraft, a good knowledge of drift angle is available, and intermittent fixes will then provide information as to the accuracy or stability of the heading reference.

While the direction of the earth's spin axis may be determined by measuring the rotational rate of the earth, this rate varies as the cosine of the latitude—becoming zero at the poles, and so small as to be unusable with present equipment above about 80° .

The horizontal component of the earth's magnetic field, which is used to determine direction, also becomes zero at the magnetic poles. In addition, the variation (i.e., the difference between true north and magnetic north) changes so rapidly with position at high latitudes that large errors arise. There is a time variation of the magnetic field which is generally small but becomes increasingly significant at high latitudes. Finally, our ability to determine true north from magnetic readings is based on our limited knowledge of the actual magnetic field.

2.1.3. PURE SYSTEMS—DEFINITIONS. Celestial. A pure celestial heading reference can vary from a hand operated sun compass or periscopic sextant to a fully automatic star tracker. In any case, the pure celestial system is useful mainly as an illustration and not as an operating system because there may be long periods when the sun or stars are not visible. To achieve precision these devices require careful installation, and can be used only during straight, level, and unaccelerated flight. Simple models are available for as little as \$20, while a completely automatic star tracker with computer stored ephemeris may cost as much as \$100,000.

Radio Celestial. The only radio celestial system constructed for aircraft was built for the United States Navy by Collins Radio in approximately the year 1958. The system incorporated a precise vertical reference, since it was to be used for radio-celestial elevation altitude as well as azimuth measurements. A requirement for an 18-inch dish creates a serious installation problem for high speed aircraft. This device was an all-weather instrument of great precision.

Magnetic. The simple remote indicating magnetic compass, found in many light aircraft, is of little use to the long distance commercial operator because of its poor performance under

and following any sort of maneuvering of the aircraft. It is mentioned here to make the listing inclusive and to indicate that its performance is not appropriate to the task under investigation.

Radio. Several radio methods are available to determine heading. Basically these are direction-finding systems. Two are tabulated for an indication of comparative performance. The Decca system provides a line of position which, with smoothing, can be flown with a zero reader when the desired course coincides with a line of position. Over a reasonable period of time this effect becomes a good indication of deviation from a desired track and thus may be used as a heading reference. The use of a radio system in conjunction with doppler navigation radars to indicate errors in a second heading reference has been suggested, but as a heading reference by itself it would be of doubtful value.

The conventional radio compass becomes a heading reference with all the errors of any radio direction-finding system. In addition, in order to determine true heading one must know his position with respect to the radio station. Accuracy is not compatible with the requirements under study.

Two-Degree-of-Freedom Directional Gyros. While accuracies are conventionally specified for directional gyros as maximum drift rates, experience shows that these are often exceeded under an operational environment. Several reasons for this discrepancy are operational environment more severe than the laboratory test conditions, inadequate maintenance of the equipment, and improper setting of the controls during flight. Gyroscopes are peculiar instruments. When not functioning properly, they may make extreme errors. In normal operation at least two free gyros are carried with some external means of checking them. In this configuration, quoted accuracy figures may be achieved.

Two-Gyro Platforms. For aircraft which undergo severe maneuvers, certain dynamic errors appear in the heading output from a two-degree-of-freedom gyro. These dynamic effects can be essentially eliminated by the use of a two-gyro platform. Such errors exist only during maneuver, and are not serious for commercial aircraft. Two-gyro platforms are discussed for completeness, although their application to the commercial field does not appear warranted.

Three-Gyro Platforms. The three-gyro platforms are discussed in this report in detail under the heading of Inertial Navigation Systems. They are mentioned here because they can provide extremely precise and useful heading references. For heading reference alone there are more economical and simpler methods available with sufficient precision for the mission. On the other hand, if an inertial system is installed in the aircraft for navigation purposes, its heading-reference properties are useful.

2.1.4. HYBRID SYSTEMS—DEFINITIONS. Composite or hybrid systems for heading reference in commercial aircraft are the rule rather than the exception. The basic reason for hybridization in the commercial case is the need for extreme reliability of operation. The most common hybrid consists of a gyro which is slaved to one of the basic sources of heading reference.

Magnetically slaved gyroscopes, as represented by the Bendix Polar Path or Sperry C-11 compasses, use the magnetic field reference to control the heading of a gyroscope. Product-improvement programs in such compasses are expected to result in better magnetic performance at high latitudes and better free-gyro performance.

Free gyros may also be slaved to celestial sources—manually and intermittently in the case of the astro-compass or periscopic sextant, or automatically and continuously in the case of the automatic star trackers. While the automatic systems have not been used by commercial carriers to date, they are in constant use by the military and have proven to be more accurate and, unfortunately, more subject to failure than the manual methods.

The free gyro operated in an earth rate direction reference mode is a true gyrocompass. It may, in the context given here, be considered a hybrid where the free gyro is slaved to the detected earth rotation rate. Gyrocompasses for aircraft are being successfully operated by the military, but will have doubtful value for commercial operators because of their complexity and consequent unreliability.

Hybridization has been carried one step further in a development by Sperry Gyroscope Company for the Navy in which a gyrocompass, a magnetic sensor, and a free gyro are combined—to be used in either the free gyro mode or one of the slaved modes.

2.1.5. APPROACH TO EVALUATION. Choice of a heading-reference system for an aircraft operating for a particular airline might be considered almost a personal matter. All of the techniques considered in this report, with the exception of radio direction finding, are basically accurate enough to satisfy the $1/3^0$ to 1^0 standard deviation criterion. Original equipment costs vary widely since there are some simple (and inaccurate) heading references available. For the accuracy specified, however, costs do not cover such a wide range, and the choice becomes more dependent upon other variables. Included among these are weight and/or volume, complexity, reliability, installation and calibration problems, performance on polar routes, performance in dynamic environments, and requirements for training of both operating and maintenance personnel. The importance of each of these variables depends upon the airline's routes, schedules, personnel, aircraft, and fiscal policies. It does not seem reasonable, for example, to prescribe the same heading reference system for every ocean-flying aircraft.

Consequently, this report makes recommendations for several competitive developments on the assumption that each of them may be useful to a particular user. No attempt is made to interrelate the variables listed in the above paragraph, although pertinent information concerning these variables is given. A discussion of the problems of heading-reference-system design is given in Section 3, Volume II.

2.1.6. CONCLUSIONS AND RECOMMENDATIONS. A number of military development programs have resulted in components which may or may not apply to commercial aircraft heading-reference systems. While these are discussed in detail in Section 3, a summary is given here in three categories: (a) those components for which a recommendation is made, (b) those which are acceptable (but not recommended), and (c) certain studies or data-taking operations which would provide information necessary to further choices.

2.1.6.1. Recommended Systems. Magnetically Slaved Gyros. It seems clear that magnetic compasses will continue to be a principal source of heading information aboard aircraft for many years. The usefulness of magnetic compasses is increased appreciably if they are calibrated properly. Calibration is easier and more complete if the compass installation was considered in the aircraft design. In connection with new aircraft development programs we recommend early consideration of the magnetic compass installation. Developments such as the miniaturized magnetic azimuth detector and an improved compass amplifier promise to be useful in future high-speed aircraft (see Section 3.3, Volume II).

Friction-Averaging Gyroscopes. Many manufacturers are making gyroscopes using the principle of rotating the bearing races in the gimbal axes. In theory and in practice this yields an appreciable decrease in the random error of a gyroscope, and the accuracy potentially available in a nonfloated friction-averaging gyroscope as a heading reference would be appropriate in combination with a doppler radar navigation system. In addition, such gyroscopes have nearly the same warm-up and maintenance characteristics as current directional gyros, and their introduction should not cause any serious problems (see Section 3.4.5, Volume II).

Electrical Compass Calibration. The calibration of aircraft magnetic compasses by "electrical" rather than physical swinging is common practice in the Air Force. For ground swinging it has the advantage of equivalent performance to the physical swinging technique at a considerable saving in time and manpower. The cost of an electrical compass calibrator is not large, and it would probably be a useful tool for commercial airlines, which depend heavily on magnetic compasses (see Section 3.3.2, Volume II).

Controller Improvement. As improved free gyros become available, corrections for the earth's rotation must be made more precisely. Present compass controllers require improvement. One convenience would be separate knobs for latitude correction and drift rate correction (see Section 3.4.5, Volume II).

Automatic Celestial Trackers. Automatic trackers would be both convenient and more precise than precise hand-operated sextants, although these advantages would come with a decrease in reliability. It is reported that one U. S. airline is planning a flight evaluation program of the Kollsman KS-85 automatic astro-tracker; the conclusions should be of interest. In addition, their availability aboard an operational aircraft would permit a more precise check of free-gyro heading references; consequently, careful test designs using the KS-85 could yield much useful information on other heading-reference performance (see Section 3.5.2, Volume II).

2.1.6.2. Acceptable Systems. Free Gyros. "Inertial quality" free gyros, in spite of their present advanced performance and decreased cost, are not recommended because they are appreciably better than required for the commercial operation. If this better performance came at no increase in cost or trouble, they would be welcome; but this is presently not the case (see Section 3.4, Volume II).

North-Seeking Gyros. North-seeking gyros are in operation and exhibit performance somewhat better than magnetically slaved gyros, but their complexity and the consequent possibility of errors resulting from undetermined failure make them unacceptable as the sole heading reference aboard an aircraft. In aircraft where a doppler inertial system exists for some other purpose, they may be a useful primary heading reference, if they can be properly monitored by a more reliable secondary system (see Section 3.6, Volume II).

Radio-Celestial Systems. These systems have the advantage of all-weather performance and great precision. In conjunction with a family of satellites they offer the possibility of periodic heading checks. However, the equipment is large, relatively complex, and expensive; for most future aircraft the advantage of being able to see through clouds does not seem to be worth the price (see Section 3.5.3, Volume II).

Ground-Based Gyrocompasses. Several fixed-base gyrocompasses have been developed and are currently in use for field artillery azimuth determination. While these instruments are not suitable for use during aircraft flight, they may be used either as a calibration aid (in swinging ship for magnetic compass deviation compensation) or in aligning a free gyro prior to flight. One instrument of this type is estimated by the manufacturer to cost \$25,000 to \$35,000 in the present army configuration (see Sections 3.3.2 and 3.4.6, Volume II).

2.1.6.3. Recommended for Future Development. Free-Gyro Performance. Operational performance data on free gyros are sparse because data have not been taken in response to a real need, and errors in the instrumentation and recording of the data are not readily identifiable. As new gyros become commercially available, carefully designed test programs will be a great aid in evaluating their potential (see Section 3.4.7, Volume II).

2.2. SUMMARY—VERY-LOW-FREQUENCY SYSTEMS

2.2.1. FRAMEWORK FOR EVALUATION. The objective of this study has been the evaluation of VLF radio navigation systems for use as long-range navigation aids for civil aviation. The systems have been evaluated in terms of an accuracy requirement of less than six nautical-mile root-mean-square radial error at ranges up to 3000 nautical miles. Operational capability has been assumed desirable in all types of aircraft up to and including Mach 3 jets. All VLF systems, whether proposed or in existence, enjoy certain common advantages—the long range of propagation permits world-wide coverage with only a few (perhaps six) stations, and the relatively stable propagation under normal conditions permits accuracy at least as good as required in this study. These systems share the disadvantage of large and expensive transmitter installations and certain propagation anomalies which leave some doubt about their usefulness of commercial aircraft.

In this report consideration is given to azimuth, range, hyperbolic-elliptical, and hyperbolic systems. Azimuth systems would be similar to Consol and are limiting (and less accurate) forms of hyperbolic systems. Range and hyperbolic-elliptical systems, which require a precise clock (1 part in 10^{11}) in the aircraft, have some potential, but have had little or no development. One attractive method for range-range systems that has been proposed is the use of existing VLF transmitters. Several such stations are now operated for communication and time-standard purposes, and some of the stations are being frequency-stabilized to a degree that meets station-synchronization requirements. The use of existing stations would greatly reduce the cost of the system. A Navy program, however, has used the station NBA in Balboa, Canal Zone, in such a dual role and has encountered many operational problems as a result.

Hyperbolic systems have received the greatest effort. DELRAC, a British program, now has the status of a propagation study and exists only on paper. The OMEGA system, which in many ways is similar to DELRAC, has been developed for the U. S. Navy and is the only VLF navigation system which has actually been operated. Consequently, major attention has been devoted to the OMEGA system, and cost and performance estimates draw heavily on this program.

2.2.2. ACCURACY CAPABILITY OF THE OMEGA SYSTEM. The accuracy analysis of the OMEGA system has shown that the maximum allowable radial root-mean-square error of six nautical miles can be provided by a three-station configuration with station baselines of from 3000 to 5000 nautical miles long, provided that the standard deviation of the time-difference measurement is less than 37 μ sec.

The evaluation of propagation data taken in the OMEGA program indicates that the time-difference measurements may be expected to have a standard deviation of about 16 μ sec. The data used to estimate components of this figure, however, were gathered at fixed locations during times of a relatively quiet ionosphere. Although the accuracy of a VLF system will often be very good, usually better than needed to meet the requirements specified here, there are times during disturbed-propagation conditions when the errors may be too great. There is the possibility that operational experience might show how to overcome or reduce them, but a system of this scope has little chance of gaining this experience from the civil aviation community prior to acceptance. While the military might find value in a system that is usually good, and inaccurate only a small percentage of the time, civil aviation would more likely accept a lower accuracy standard if there were assurance that the errors would never exceed some fixed limit.

In the available error data certain errors are currently considered to be random although they are likely to be constant over large areas and extended periods of time. For example, sudden ionospheric disturbances (SID's) cause a maximum error in time difference of 30 to 40 μ sec. It is possible that in an operational system some means could be employed to reduce these errors appreciably. In the LORAN-C and DECCA systems a field monitor is often placed in the service area to keep the hyperbolic coordinates of that point constant by remote adjustment of the phase of the slave transmitters. This practice reduces errors over a large portion of the service area. It is anticipated that such a technique will be useful in the VLF region, although proof will not be available until the system has been in actual operation for some time. If the U. S. Navy does install and operate a full OMEGA system, such proof should be forthcoming within a few years.

Errors resulting from anomalous propagation due to a disturbed ionosphere may exceed the six-mile accuracy requirement. Although such errors may not occur frequently, they may sometimes persist for several hours at a time or over an entire flight. Such errors cannot be fully evaluated until more propagation information becomes available. Particular areas that require more investigation are SID's, magnetic storms, arctic and auroral propagation, meteor showers, and east-vs.-west propagation time. Further, it is clear that propagation research is now lacking in accuracy and reliability. That is, we can show that the accuracy usually should be very good, but we cannot prove that the errors will not be occasionally excessive. Unfortunately, the propagation investigations necessary to secure such information may require a long period of time.

2.2.3. THE LANE-RESOLUTION PROBLEM. A more serious problem with the OMEGA system is that of lane resolution. As with many phase-measurement systems an ambiguity in

readout exists every 360° . For the OMEGA system operating at 10.2 kcs the ambiguity occurs approximately every eight miles in a direction normal to the hyperbolic lines-of-position.

Although a technique for ambiguity resolution has been proposed, the dispersive properties of VLF propagation leave some doubt whether a practical system can be implemented. Little activity toward this end is in progress, since the Navy expects the system to provide lane resolution by dead reckoning for surface ships.

For aircraft it is unlikely that dead reckoning will be reliable enough to permit this technique for lane identification. Data from operation of the OMEGA system over a period of time will undoubtedly permit a conclusion on the lane-identification problem, but such data are not available now.

2.2.4. READOUT FOR THE OMEGA SYSTEM. The readout of the present experimental OMEGA airborne receiver is a strip-chart recorder; hyperbolic coordinates are transformed to geographic coordinates on charts similar to LORAN-A charts. If the readout required in future airline operation is a real time indication of geographic coordinates, a computer will be required for coordinate conversion. Such an airborne computer with sufficient accuracy is not yet available. The present OMEGA airborne receiver developed by the Naval Research Laboratories requires external rate information on the radial velocity of the receiver relative to each station. The velocity information must be accurate to ± 250 knots. Although this is not a stringent requirement and can be furnished by standard airspeed indicators and heading references (including wind drift), a computer would again be required to compute the radial components of velocity and to correct for diurnal variations.

2.2.5. COST OF THE OMEGA SYSTEM. The estimated cost of a production version of the present OMEGA receiver ranges from eight to ten thousand dollars. A receiver with a lane identification, or ambiguity resolution, would cost nearly twice this amount. The cost of a computer can only be estimated since none have been developed; however, the cost might be considerably more than that of the receiver. The costs of transmitter stations have been estimated at from ten to thirty million dollars.

2.2.6. APPLICATION OF VLF SYSTEMS FOR OVER-OCEAN NAVIGATION. VLF systems, particularly the hyperbolic type exemplified by OMEGA, have many real advantages for long-range over-ocean navigation. As pointed out in the first paragraph of this section, the long range of propagation in this frequency region, the stability of the phase relationships, and the possibility of world-wide coverage over ocean and land with only a few transmitters make VLF an attractive possibility. While the initial cost is high, there are few repetitive major costs such as might be incurred by a satellite system. Furthermore, the possibility of time sharing existing communications stations would allow some cost sharing.

Several problems make the introduction of operational VLF systems unlikely between 1965 and 1975. The propagation research necessary to insure acceptable operation under all states of the ionosphere and in all areas may require several years. No solution of the ambiguity-resolution problem has been conclusively demonstrated; here, again, considerable experimentation will be required. The airborne computer required for coordinate conversion is not available and may require some time to develop. Finally, the requirement for stations on foreign soil will almost surely raise diplomatic problems that have required years to solve in the past.

2.3. SUMMARY—INERTIAL SYSTEMS

The results of this investigation show that inertial techniques may be used in commercial applications with a reasonable degree of success, depending upon the allowable positional error, the accuracy and availability of external positional information for the longer flight times, and of course system reliability. External positional information can be obtained by radio techniques, landmarks, ships with known positions, celestially derived positions, or some combination of these methods.

Inertial navigational equipment has the advantage of high accuracy for short-term flights, which makes this method more useful as aircraft speed increases. In addition, continuous positional information, which becomes more important as speed increases, is available from an inertial system. With this increasing speed it becomes more desirable to control the aircraft autopilot automatically by comparing the inertially derived information with the desired course information to derive the autopilot control signals.

In the past inertial costs have been prohibitive. At present they are much lower, and in the near future inertial systems will compare economically with other self-contained systems. Accuracy improvement in recent years has been appreciable, and as aircraft speed increases the accuracy of inertial systems will be very favorable on present commercial routes. It is doubtful that inertial systems will prove preferable to doppler systems in current propeller aircraft. Both accuracy and reliability will require a back-up navigation system which in itself would suffice (except for convenience) as the primary navigation system. In subsonic jets the circumstances are similar. In future supersonic transports the increased speed and reduced flight times make an inertial system attractive for accuracy and continuous-position information. However, a back-up navigation capability will still be required to monitor the inertial system and provide an emergency capability.

The high cost of inertial systems and their support will probably be justified only for the next generation of aircraft. However, in order to fully assess inertial potential for supersonic transports it is important that experimental and operational tests be conducted in present aircraft. This could be accomplished by consigning systems to air carriers for use on present

aircraft and routes. Close cooperation between the Federal Government, inertial manufacturers, and airlines in operational testing and inertial-system improvement from 1962 to 1965 can result in an excellent navigation system utilizing inertial and other techniques for next generation aircraft between 1965 and 1975. Such operational testing is best accomplished over transcontinental domestic routes, where instrumentation and support facilities are readily available, rather than on overseas routes.

A decision which needs to be made is the choice between pure-inertial and doppler-inertial systems. Systems are available having accuracies ranging from one to three nautical miles per hour CEP (Circular Probable Error). Pure-inertial systems cover the accuracy range from two to three nautical miles per hour, while the doppler-inertial system, according to manufacturers' published graphs and specifications, possesses the higher accuracy starting from one nautical mile per hour. Another advantage the doppler-inertial system has over the pure-inertial system is the third-order gyrocompass mode of operation during a flight. Either system can be operated in the gyrocompass mode in the ground check-out or alignment procedure, but an accurate ground-track velocity reference is needed during a flight in order to take advantage of the gyrocompass mode of operation. The gyrocompass heading-reference error is bounded with the magnitude a function of gyro drift, accelerometer drift, integrator drift, and alignment errors. The free-gyro north reference, encompassed in the pure-inertial system, has an unbounded heading-reference error which increases with time, the rate being a function of gyro drift, alignment errors, etc. Furthermore, such hybrid systems can be designed in such a manner that in the event of an inertial failure the system could be operated as a combined doppler, magnetic compass, and computer system with a reduced navigational accuracy. Similarly, if a failure occurred in the doppler system, the navigation could be handled by the pure-inertial mode.

Since the late 1940's progress in inertial technology has been phenomenal. While inertial systems are still too expensive and lack sufficient accuracy and reliability for immediate application, these shortcomings are nearly marginal. Progress in the near future should result in systems that will be suitable for consideration in next-generation aircraft.

2.4. SUMMARY—SATELLITE SYSTEMS

Section 6, Volume II, describes and analyzes three possible methods of applying earth satellites to the problem of long-distance navigation with respect to cost and performance, and then presents conclusions.

In all methods of using satellites for navigation purposes, information on the position of the satellite relative to the earth as a function of time would be communicated to the navigating

vehicle in some manner, possibly from the satellite itself. The navigation system would then determine the position of the aircraft with respect to the satellite at a known time. By combining this with the known position of the satellite, the aircraft's position in earth coordinates could be computed. In most navigation methods accurate values of aircraft velocity and altitude must be available to the navigator for use in computing position. Optical methods of determining the position of the satellite by the aircraft would be useful only in good weather. For an all-weather navigation system some type of radar or radio link between the satellite and the aircraft is required.

There are two general methods of using a satellite for aircraft navigation purposes. In one method information relating aircraft position to satellite position would be obtained. This might be information on aircraft position with respect to two or more satellites at a single instant or a single satellite at two or more instants. From this information the position of the aircraft could be fixed with respect to the known satellite position at the instants of measurement.

One variation of this method measures distances from the satellites to an aircraft by using pulse signals from the satellite to measure time differences by means of accurate electronic clocks in both the aircraft and the satellites.

Another variation measures the doppler shift of a radio signal transmitted from the satellite. This particular variation is the basis for the Transit system, currently being developed and tested by the Applied Physics Laboratory of The Johns Hopkins University under sponsorship of the U. S. Navy Bureau of Naval Weapons.

A basically different method of determining aircraft position would be to use the satellite as a celestial body. The navigation system of the aircraft would make angular measurements to determine the direction of the satellite with respect to vertical or horizontal earth references. This is similar to conventional celestial navigation.

Some methods of aircraft navigation which involve the use of earth satellites appear to be economically and technically feasible. Satellites would be capable of handling any volume of traffic, and would provide world-wide all-weather coverage. If used with random rather than synchronized orbits, they would provide a noncontinuous position-fixing capability which would have to be combined with dead-reckoning methods. In this manner, it would be possible to determine aircraft position with an error whose d_{rms} value remained in the two- to six-nautical-mile range. For certain methods the user's equipment would not be excessively large or expensive. Overall system reliability may be open to some question pending an actual system demonstration. For all the systems substantial installations of ground-based and satellite equipment would be required to make the method available for air navigation purposes.

The Transit system is now under development, and one using four satellites is scheduled to be operational in 1963. More detailed information concerning its cost and performance will become available as the program proceeds. For each of the other methods a program of research and development is needed to bring it to its full capability. Detailed analytical studies of particular systems can be made at limited expense. An experimental demonstration using satellites launched for other purposes would cost from \$250,000 to \$350,000. A complete experimental demonstration of feasibility would cost from \$5,000,000 to \$7,000,000.

The characteristics of three navigation methods which use earth satellites are presented in Table III (Table XIX, Section 6, Volume II, is an expanded version).

The conclusions of this report can also be stated by the specifications contained in the contract statement of work. Satellite methods of navigation could be available for introduction and use only during the latter part of the 1965-1975 time period, Transit being the system which would be available earliest. With respect to fix-renewal interval, the Transit system, even if expanded to eight satellites, would not meet the requirement for a fix renewal every 500 nautical miles for aircraft at speeds higher than Mach 1. The other methods considered could in general meet this requirement except for occasional coverage gaps. All systems could be capable of providing position fixes with d_{rms} values of three nautical miles or less.

Besides their uses for aircraft navigation purposes, satellite navigation systems could have other applications. One of these might be to provide geodetic positioning, which would allow very accurate determination of the relative location of points on the earth's surface. Another might be the synchronization of clocks throughout the world. Airborne angle-measuring systems would also be able to perform the functions of inertial navigation, heading reference, and attitude reference.

The results and conclusion of this study of navigational satellites are necessarily based on incomplete information; hence, it would be desirable to continuously review additional information as it becomes available. Since the development and evaluation of navigational satellites is being actively pursued at present, more detailed and conclusive data will be forthcoming soon. But unless major advances are reported, it is not likely that the conclusions of this report will be substantially changed.

If research and development beyond currently active programs is undertaken, we recommend that it should be initially confined to relatively small-scale efforts directed primarily toward investigating the critical factors which are likely to affect proposed systems. Such an investigation would probably be less expensive than a full-scale test program.

The conclusions in this report have been based solely on the conditions representative of commercial aircraft flight. They cannot necessarily be extended to other applications.

TABLE III. COMPARISON OF NAVIGATION SATELLITE SYSTEMS

NOTE: Coverage data are based on random, rather than synchronized, orbits. Spare equipment is not included in cost estimate.

Measurement Method	Doppler	Angle	Range-Difference
Status		Proposal (user's equipment partly developed)	Proposal
Number of Satellites	8	8	12
Performance at 45° Latitude			
Accuracy of Fix (d_{rms} in n mi)	1.5 to 2.5	2	1
Accuracy with 3 n mi/hr Inertial System (d_{rms})	3.0	2.5	2.0
Satellite Characteristics			
Ground-based System	Moderately complex	Simple	Moderately complex
User's Equipment (Airborne)	Extensive	Moderate	Moderate
Size (cu ft)	3 to 5	15 to 20	2 to 3
Weight (lb)	100 to 125	300 to 375	75 to 100
Cost (\$)	20,000 to 30,000	20,000 to 30,000 (exclusive of vertical reference system)	10,000 to 12,000
Complexity	Moderate	High	Moderate

Appendix A

STATEMENT OF WORK

A. 1. INTRODUCTION

The work to be accomplished under the tasks set forth herein includes reviewing the state of the art and development potential for each of several selected navigation aids or techniques, compiling and analyzing these data, and answering pertinent questions which are asked in each case. The results of this work will be provided in a report to the Research Division of the FAA, Systems Research and Development Service. This project is part of a larger program being carried on by various segments of the FAA Systems Research and Development Service under the program title LODISNAV. As part of this larger program the Research Division is also performing studies, in the house, on other advanced navigation techniques. The data accumulated under this contract will be combined with the results of its in-the-house work by the Research Division of the Systems Research and Development Service.

A. 2. GENERAL BACKGROUND

The LODISNAV Program Plan includes a technical evaluation of existing and potential navigation aids to serve as a basis for choosing and developing long distance navigation aids and to assist in achieving international agreement through ICAO on facilities and procedures for over-ocean (and possibly high-altitude over-continent) use. It also includes determination of required system accuracy standards and required operational and procedural characteristics of such navigation aids.

However, work to be performed by the Contractor is restricted to the specific navigational "systems" and techniques as enumerated in the tasks under Section A.3, including a determination of the "field" accuracy and coverage which can be predicted and the technological (or allied) problems which will have to be solved in order to permit introduction within the time period indicated in each case. Work relates to the techniques usable by nonmilitary ocean-crossing aircraft. The approximate quantitative maximum and minimum accuracy figures (and, where applicable, other characteristics), which encompass the anticipated requirements for each technique used, are specified herein.

A. 3. SPECIFIC TASKS

The Contractor shall provide all necessary qualified personnel, facilities, materials, equipment, and services to accomplish the following tasks.

A.3.1. IMPROVED HEADING REFERENCES FOR NONMILITARY OCEAN-CROSSING AIR-CRAFT. Since all of the navigation systems now being considered for long distance use involve a heading reference and since in many systems the major errors expected are due to the heading reference, the data sought in this task are basic to studies of the characteristics of all of these systems. Development objectives for heading references to be used for military aircraft, missiles, and space vehicles have long been for devices which have an order of accuracy (or drift rate) one, two, or even three magnitudes better than are needed for the applications of interest under this work statement. A relatively cheap design and production technique which has been discarded as of little interest for military or space applications might well prove to be the solution to the problem of obtaining a much more reliable "relatively low accuracy" heading reference if reexamined.

The Contractor shall make a critical review and analysis of both the state of the art and the development potential for improving heading references for at least the following:

- Magnetically-slaved Gyros
- Free Gyros
- North-seeking Gyros
- Magnetic References (for slaving)
- Variation Correction

The time period (for use and/or introduction into service) to be considered shall be from the present until 1975.

Such review and analysis shall include techniques for various maximum flight times up to approximately 15 hours and techniques for attaining practical devices whose errors (including drift) are such as to provide true heading knowledge (averaged over the time of flight being considered) with error spreads having standard deviation values within the range from $1/3^{\circ}$ to 1° .

After such review and analysis the Contractor shall determine the answers to at least the following questions:

- (a) What techniques are available or can be developed for the time period specified which will provide practical, easily maintainable, and economical equipment within the heading accuracy range specified?
- (b) What are the predicted characteristics, costs, and time of availability?
- (c) What technological problems or problems of introduction or use can be anticipated?
- (d) How great are these problems?

- (e) What is required to accelerate the introduction and use by nonmilitary aircraft of heading devices which employ techniques previously developed for military or space applications?

The Contractor shall spend approximately 35% of his total effort on this task.

A.3.2. VERY-LOW-FREQUENCY GROUND-BASED TECHNIQUES. The Contractor shall make a critical review and analysis of both the state of the art and the development potential of ground-based long distance navigation aids operating at very low frequencies (below 50 kc). Examples of such systems are DELRAC and OMEGA. The time period (for use and/or introduction into service) to be considered shall be from 1965 to 1975.

Such review and analysis shall include those techniques appropriate for both over-ocean and over-land use. The maximum distance from the ground facilities within which use may be desired shall be considered as approximately 3000 nautical miles. Techniques which do not permit use (within the specified accuracy range) at distances of at least 1000 nautical miles shall not be analyzed in detail. Techniques providing airborne knowledge of position with maximum radial error spreads (at the most unfavorable position within the coverage considered) having values within the range from 2 to 6 nautical miles shall be included.

The following questions shall be included among those answered by the Contractor under this task:

- (a) What techniques are available or can be developed which will provide a practical and economical system for the various significant combinations of coverage and accuracy chosen from the ranges specified above?
- (b) What are the predicted characteristics, costs, and time of availability?
- (c) What technological problems or problems of introduction or use can be anticipated?
- (d) How great are these problems?

The Contractor shall spend approximately 20% of his total effort on this task.

A.3.3. INERTIAL NAVIGATION TECHNIQUES. The Contractor shall make a critical review and analysis of both the state of the art and the development potential of inertial navigation techniques (and doppler-aided inertial, if time permits) which might be developed for use by nonmilitary aircraft when flying over-ocean and high-altitude, over-continent routes. The time period (for use and/or introduction into service) to be considered shall be from 1965 to 1975.

This work shall include inertial techniques which would cover aircraft with maximum flight distances of 1500 to 5000 nautical miles and flight times of up to twelve hours and which would provide airborne knowledge of position with maximum radial error spreads having d_{rms} values within the range from 2 to 6 nautical miles.

The following questions shall be included among those answered by the Contractor under this task:

- (a) What techniques are available or can be developed (for the time period specified) which will provide a practical and economical system for the various significant combinations of the maximum flight distance, maximum flight times, and maximum radial error spreads chosen from the ranges specified above?
- (b) What are the predicted characteristics, costs, and time of availability?
- (c) What technological problems or problems of introduction or use can be anticipated?
- (d) How great are these problems?

The Contractor shall spend approximately 25% of his total effort on this task.

A.3.4. AIRCRAFT NAVIGATION USING EARTH SATELLITES. The Contractor shall make a critical review and analysis of both the state of the art and the development potential of earth satellites as aircraft long distance navigation aids over ocean areas and at high altitudes over continents. Examples of aids proposed or under development are the Pathfinder Navigation System (U. S. Navy Hydrographic Office Technical Report No. TR-71) and Project Transit. The time period (for use and/or introduction into service) to be considered shall be from 1965 to 1975.

The work shall cover techniques which provide positional data (essentially everywhere over the earth) to aircraft types with various maximum speeds up to Mach 3. Position fixes should at least be renewable within an interval not to exceed the time in which the aircraft with the maximum speed considered travels 500 nautical miles. Systems for aircraft with several different maximum speeds and the problems introduced by the aircraft's altitude and velocity shall be analyzed. Techniques shall be included which are capable of providing position fixes (utilizing the satellite) with maximum radial error spreads having d_{rms} values ranging from 1 to 3 nautical miles; or if the position data (using the satellite) are renewable within less than 300 nautical miles of travel by the maximum-speed aircraft considered, radial error spreads having d_{rms} values of as much as approximately 5 nautical miles shall be included.

The following questions shall be included among those answered by the Contractor under this task:

- (a) What techniques are available or can be developed (for the time period specified) which will provide a practical and economical navigation aid for the various significant combinations of maximum aircraft speeds, fix renewal interval, and radial error spreads chosen from within the range of values specified above?
- (b) What are the predicted characteristics, costs, and time of availability?
- (c) What technological problems or problems of introduction or use can be anticipated?
- (d) How great are these problems?

The Contractor shall spend approximately 20% of his total effort on this task.

Appendix B
LETTER SUMMARY

Federal Aviation Agency
Aviation Research and Development Service
Contracts Division
T-5 Building
16th and Constitution Ave., N. W.
Washington 25, D. C.

31 July 1962

Attn: Mr. E. E. Grover

Dear Sir:

Reference: FAA Contract No. ARDS-436 .

In accordance with paragraph D-ii of the Schedule of Contract ARDS-436 6 copies of a draft of the final report are being submitted herewith to your office. Concurrently we are submitting 2 copies of the report, along with a copy of this letter, to Mr. N. Braverman, the Project Manager. A short abstract of the report is included at the beginning of each copy.

Inasmuch as the Federal Aviation Agency may wish to suggest changes or modifications in this report it has not been typed in final form. Final editing and typing for reproduction will be executed upon return of the draft copies to the University.

Information excluded from the final report but which may be useful to the Project Manager is that concerning several classified inertial navigation system developments. A brief review of this material, which may be read in conjunction with the inertial section of this report, will be forwarded under separate cover by letter to the Project Manager.

Paragraph D-ii of the Contract Schedule calls for conclusions and recommendations resulting from this study to be included in this cover letter. These conclusions and recommendations are given in the summary section of the report (Section 2) and are restated here.

Heading-Reference Systems

Magnetic compasses will continue to be a principal source of heading information aboard aircraft for many years. In connection with new aircraft development programs, early consideration of the magnetic compass installation is recommended. Developments such as the miniaturized magnetic azimuth detector and an improved compass amplifier promise to be useful in future high speed aircraft.

The accuracy potentially available in a non-floated friction averaging gyroscope as a heading reference would be appropriate in combination with a doppler radar navigation system. In addition, such gyroscopes have nearly the warm up and maintenance characteristics of current directional gyros and should not cause any serious introduction problems.

The calibration of aircraft magnetic compasses by "electrical" rather than physical swinging would probably be useful for commercial airlines which depend heavily on magnetic compasses.

As improved free gyros become available, corrections for earth's rotation must be made more precisely. Present compass controllers require improvement. One convenient item would be separate knobs for latitude correction and drift-rate correction.

Automatic celestial trackers would be both convenient and more precise than present hand operated sextants, although these advantages come with some decrease in reliability. In addition, the availability of this equipment aboard an operational aircraft should permit a more precise check of free gyro heading references.

"Inertial quality" free gyros, in spite of their present advanced state of performance and relatively low cost, are not recommended because they are appreciably better than required for the commercial operation.

While north-seeking gyros are in operation and exhibit performance somewhat better than magnetically slaved gyros, their complexity and consequent possibility of errors resulting from undetermined failure make them unacceptable for the sole heading reference aboard an aircraft.

Radio-celestial systems offer the possibility of periodic heading checks in all weather. However, the equipment is large, relatively complex, and expensive, and for the majority of future aircraft the advantage of being able to see through clouds does not seem to be worth the price.

Operational performance data on free gyros are sparse. This situation exists because data have not been taken in response to a real need, and errors in the instrumentation and recording of the data are not readily identifiable. As new gyros become available for commercial operation, carefully designed test programs would be a great aid in evaluating their potential.

Very-Low-Frequency Systems

Range-measuring, azimuth-measuring, and hyperbolic-elliptical very-low-frequency systems have been proposed in the past, but the only real experimental effort toward a system has been in connection with the hyperbolic system, OMEGA. The analysis of the OMEGA development has shown that the accuracy required for commercial over-ocean navigation can be provided by a station configuration with station baselines of from 3000 to 5000 nautical miles in length under normal propagation conditions. Propagation anomalies may cause the error to be greater than allowable, although current programs aimed at understanding these anomalies have a good chance of reducing the errors back to an acceptable value. The most serious problem, from the standpoint of commercial aviation, is that the lane resolution problem for hyperbolic systems in this

frequency region has not been satisfactorily solved. Only experimental readout equipment exists, and this would not be satisfactory for a commercial operation. Although the initial cost of the system is high, repetitive costs are not large and the system is close to being economically feasible for commercial aviation.

Several problems make the introduction of VLF systems on an operational basis unlikely within the 1965-75 time period. The propagation research necessary to insure acceptable operation under all states of the ionosphere and in all areas may require several years. A solution of the ambiguity resolution problem has not been conclusively demonstrated and here again considerable experimentation will be required. The airborne computer required for coordinate conversion is not available and may require some time to develop. Lastly, the requirement for stations on foreign soil will almost surely raise problems of a nature that have required years to solve in the past.

Inertial Systems

It is concluded that inertial navigation systems are competitive with Doppler navigation systems accuracy and performance wise, but that these qualities do not overshadow the cost considerations for the present aircraft. An airline would have to be convinced of the increased convenience, adequate reliability, and moderate costs before inertial systems will find wide acceptance for sub-sonic jets.

The recent trends in lowered cost make the inertial system most attractive for future super-sonic aircraft, either as a pure inertial system or possibly as a Doppler-inertial system. Commercial operational experience with today's aircraft would be desirable in order to determine the usefulness of inertial systems. It is recommended that an experimental evaluation of a current inertial system be conducted, using aircraft flying over land rather than ocean routes so that good experimental accuracy data can be obtained.

Many of the objections to inertial systems, such as long warmup times, difficult alignment procedures, poor reliability, initial and maintenance costs, have been at least partially resolved. The relatively mass production of at least one platform indicates that more operational problems will also be reduced in the near future.

Satellite Systems

Methods of aircraft navigation by means of satellites appear to be economically and technically feasible. Such systems would be capable of handling any volume of traffic, and would provide world-wide all-weather coverage. If used with random, rather than synchronized orbits, they would provide a position-fixing capability which is not continuous but must be combined with dead-reckoning methods. In this manner, it would be possible to navigate the aircraft with an

error whose d_{rms} value remained in the 2- to 6-nautical-mile range. For certain methods the user's equipment would not be excessively large or expensive. Overall system reliability may be open to some question pending an actual system demonstration. For all the systems, substantial installations of ground based and satellite equipment would be required to make the method available for navigation purposes.

Satellite methods of navigation should be available for introduction and use only during the latter part of the 1965-75 time period, Transit being the system which would be available earliest. With respect to fix renewal interval, the Transit system, even if expanded to eight satellites from the presently planned four, would not meet the requirement for a fix renewal every 500 nautical miles for aircraft at speeds higher than Mach 1. The other methods considered, which are not under active development, would in general meet this requirement except for occasional coverage gaps.

If future research and development of satellite navigation methods is to be undertaken beyond currently active programs, it is recommended that these should initially be confined to relatively small scale efforts directed toward the critical factors which are likely to affect the success or failure of the proposed systems.

Very truly yours,

James O'Day, Head
Navigation and Guidance Laboratory

Enclosures
6 copies Final Report draft

cc. N. Braverman

REFERENCES

1. TWA Navigation Symposium Record, January 8, 1962.
2. R. N. White, "Airborne Doppler Radar Navigation of Jet Transport Aircraft," IRE Transactions on Aerospace and Navigational Electronics, March 1962, Vol. ANE-9, No. 1, pp. 11-20.
3. D. C. Willis, Operational Experience with Doppler, Institute of Navigation Meeting, June 1962 (to be published).

DISTRIBUTION LIST

<u>Copy No.</u>	<u>Addressee</u>
1-200	Chief
(1 repro)	General Service Branch
	RD-94
	Aviation Research and Development Service
	Washington 25, D. C.

Div. 19

Inst. of Science and Technology U. of Mich., Ann Arbor
STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAV-
IGATION TECHNIQUES, Volume I: Summary, Final Report, by
James O'Day, Irvin Sattinger, Robert Scott, and Joseph Sullivan.
Dec. 62. 31 p. incl. illus., 3 refs.
(Report No. 4761-10-F(I))
(Contract ARDS-436)

The state of the art and the development potential of heading
references, VLF radio systems, inertial techniques, and
satellite systems have been considered for their applicability
to long-range ocean-crossing nonmilitary aircraft from 1965
to 1975. The navigation systems discussed here are by no
means the only competitors for position and course deter-
mination over transoceanic and high-altitude transcontinent-
al regions; our data and information should permit further
comparison with other systems. (over)

UNCLASSIFIED

- I. O'Day, James;
Sattinger, Irvin;
Scott, Robert; and
Sullivan, Joseph
- II. Federal Aviation
Agency
- III. Contract ARDS-
436

Div. 19

Inst. of Science and Technology U. of Mich., Ann Arbor
STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAV-
IGATION TECHNIQUES, Volume I: Summary, Final Report, by
James O'Day, Irvin Sattinger, Robert Scott, and Joseph Sullivan.
Dec. 62. 31 p. incl. illus., 3 refs.
(Report No. 4761-10-F(I))
(Contract ARDS-436)

The state of the art and the development potential of heading
references, VLF radio systems, inertial techniques, and
satellite systems have been considered for their applicability
to long-range ocean-crossing nonmilitary aircraft from 1965
to 1975. The navigation systems discussed here are by no
means the only competitors for position and course deter-
mination over transoceanic and high-altitude transcontinent-
al regions; our data and information should permit further
comparison with other systems. (over)

UNCLASSIFIED

- I. O'Day, James;
Sattinger, Irvin;
Scott, Robert; and
Sullivan, Joseph
- II. Federal Aviation
Agency
- III. Contract ARDS-
436

Div. 19

Inst. of Science and Technology U. of Mich., Ann Arbor
STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAV-
IGATION TECHNIQUES, Volume I: Summary, Final Report, by
James O'Day, Irvin Sattinger, Robert Scott, and Joseph Sullivan.
Dec. 62. 31 p. incl. illus., 3 refs.
(Report No. 4761-10-F(I))
(Contract ARDS-436)

The state of the art and the development potential of heading
references, VLF radio systems, inertial techniques, and
satellite systems have been considered for their applicability
to long-range ocean-crossing nonmilitary aircraft from 1965
to 1975. The navigation systems discussed here are by no
means the only competitors for position and course deter-
mination over transoceanic and high-altitude transcontinent-
al regions; our data and information should permit further
comparison with other systems. (over)

UNCLASSIFIED

- I. O'Day, James;
Sattinger, Irvin;
Scott, Robert; and
Sullivan, Joseph
- II. Federal Aviation
Agency
- III. Contract ARDS-
436

Div. 19

Inst. of Science and Technology U. of Mich., Ann Arbor
STUDY AND ANALYSIS OF SELECTED LONG-DISTANCE NAV-
IGATION TECHNIQUES, Volume I: Summary, Final Report, by
James O'Day, Irvin Sattinger, Robert Scott, and Joseph Sullivan.
Dec. 62. 31 p. incl. illus., 3 refs.
(Report No. 4761-10-F(I))
(Contract ARDS-436)

The state of the art and the development potential of heading
references, VLF radio systems, inertial techniques, and
satellite systems have been considered for their applicability
to long-range ocean-crossing nonmilitary aircraft from 1965
to 1975. The navigation systems discussed here are by no
means the only competitors for position and course deter-
mination over transoceanic and high-altitude transcontinent-
al regions; our data and information should permit further
comparison with other systems. (over)

UNCLASSIFIED

- I. O'Day, James;
Sattinger, Irvin;
Scott, Robert; and
Sullivan, Joseph
- II. Federal Aviation
Agency
- III. Contract ARDS-
436

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED	<p>We conclude that magnetically slaved and good free gyroscopes will continue to be the principal heading references for commercial aircraft; we recommend improvement programs in magnetic compasses and the use of nonfloated friction-averaging gyros. We do not expect that VLF systems will have been sufficiently operated to be acceptable for commercial aviation before 1975. However, their inherent accuracy and ability to cover large areas make them attractive if certain propagation and instrumentation errors can be solved. In their present form inertial systems are competitive with doppler navigation systems, at least in accuracy. The choice of an inertial system for commercial flight depends on cost, reliability, and convenience. Product improvement and the recently lowered cost of inertial platforms may make these systems attractive in the near future, particularly for higher speed aircraft. The present configuration of Transit, the only satellite reference system scheduled for implementation, exhibits time gaps which would be serious for aircraft use. The single-fix accuracy appears adequate if additional satellites are orbited to provide more frequent fixes.</p>	UNCLASSIFIED	<p>Automatic navigators Bearing finding Celestial navigation Doppler navigation Hyperbolic navigation Inertial navigation Radio navigation Space navigation</p>
UNCLASSIFIED		UNCLASSIFIED	<p>Automatic navigators Bearing finding Celestial navigation Doppler navigation Hyperbolic navigation Inertial navigation Radio navigation Space navigation</p>

+

UNCLASSIFIED	<p>We conclude that magnetically slaved and good free gyroscopes will continue to be the principal heading references for commercial aircraft; we recommend improvement programs in magnetic compasses and the use of nonfloated friction-averaging gyros. We do not expect that VLF systems will have been sufficiently operated to be acceptable for commercial aviation before 1975. However, their inherent accuracy and ability to cover large areas make them attractive if certain propagation and instrumentation errors can be solved. In their present form inertial systems are competitive with doppler navigation systems, at least in accuracy. The choice of an inertial system for commercial flight depends on cost, reliability, and convenience. Product improvement and the recently lowered cost of inertial platforms may make these systems attractive in the near future, particularly for higher speed aircraft. The present configuration of Transit, the only satellite reference system scheduled for implementation, exhibits time gaps which would be serious for aircraft use. The single-fix accuracy appears adequate if additional satellites are orbited to provide more frequent fixes.</p>	UNCLASSIFIED	<p>Automatic navigators Bearing finding Celestial navigation Doppler navigation Hyperbolic navigation Inertial navigation Radio navigation Space navigation</p>
UNCLASSIFIED		UNCLASSIFIED	<p>Automatic navigators Bearing finding Celestial navigation Doppler navigation Hyperbolic navigation Inertial navigation Radio navigation Space navigation</p>